

The Predictive Simulation of Exhaust Pipe Narrow-band Noise

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ABSTRACT

A method of predictive simulation of flow-induced noise using computational fluid dynamics has been developed. The goal for the developed method was application in the vehicle development process, and the target of the research was therefore set as balancing the realization of a practical level of predictive accuracy and a practical computation time. In order to simulate flow-induced noise, it is necessary to compute detailed eddy flows and changes in the density of the air. In the research discussed in this paper, the occurrence or non-occurrence of flow-induced noise was predicted by conducting unsteady compressible flow calculation using large eddy simulation, a type of turbulence model. The target flow-induced noise for prediction was narrow-band noise, a type of noise in which sound increases in specific frequency ranges. Assuming the area of generation of flow-induced noise to be the exhaust pipe, including the complex shape of the muffler, predictive accuracy was verified under conditions that modeled measurements in steady-state flow test equipment. In order to reduce computation time while maintaining predictive accuracy, calculation methods were combined and computation times compared. This made it possible to reduce computation time by 61% against that in the initial stage of development of the method. In addition, a study utilizing multiple exhaust pipe shapes indicated that a correlation existed between the number of computation cells and computation time. The developed method has made it possible to predict the occurrence of narrow-band noise within a practical computation time.

CITATION: Kanai, K. and Katsuyama, H., "The Predictive Simulation of Exhaust Pipe Narrow-band Noise," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1329.

INTRODUCTION

Demands for passenger comfort are increasing in the automotive market together with demands for fuel efficiency and dynamic performance. The reduction of noise in the vehicle cabin is desirable from the perspective of increasing comfort. Automobiles present a variety of noise sources, including engine noise and air flow-induced noise produced by exterior fittings. The exhaust pipe is also a noise source. The research discussed in this paper focused on exhaust-related flow-induced noise. (The combination of the exhaust pipe and the muffler will be collectively termed the "exhaust pipe" in this paper). The exhaust pipe has the role of silencing noise from the engine, but the noise-silencing structures in themselves are responsible for the generation of noise. Flow-induced noise from the exhaust pipe can be divided into two types: broad-band noise and narrow-band noise (Fig. 1). In the case of broad-band noise, sound pressure increases across a broad frequency range, as shown in Fig. 1(a). The noise known as wind roar is this type of noise. In the case of narrow-band noise, sound pressure increases only at specific

frequencies, as shown in Fig. 1(b). Narrow-band noise produces a sound like whistling. Because of this, vehicle occupants tend to be aware of narrow-band noise, and it represents an issue from the perspective of commercial appeal.

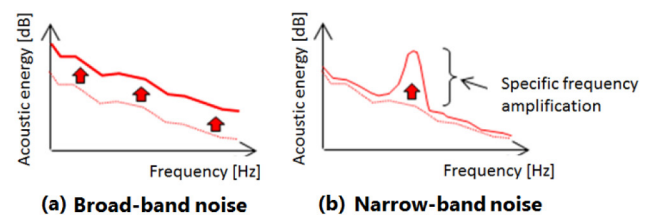


Figure 1. Classification of flow-induced noise

Narrow-Band Noise

Figure 2 shows the results of noise measurements in an exhaust pipe. The results show that sound pressure is higher at close to 3,800 Hz than in other frequency domains when engine speed is between 5,000

and 6,000 rpm. This is narrow-band noise. Exhaust noise is made up of a variety of types of noise, including noise produced by flows, noise produced by sudden differences in temperature, and noise produced by the vibration of structures. Flow-induced noise in the exhaust system is generated when the exhaust pulse from the engine changes with engine speed, changing the flow in the exhaust pipe. It is thought that when narrow-band noise is being generated, cyclical fluctuations in volume are occurring due to typical structures in the interior of the exhaust pipe. Under certain flow-speed conditions, there is mutual interference between cyclically generated vortices, producing cyclical fluctuations in pressure. These pressure fluctuations result in the generation of noise due to phenomena such as edge tone or cavity tone creation at the various structures inside the exhaust pipe(1).

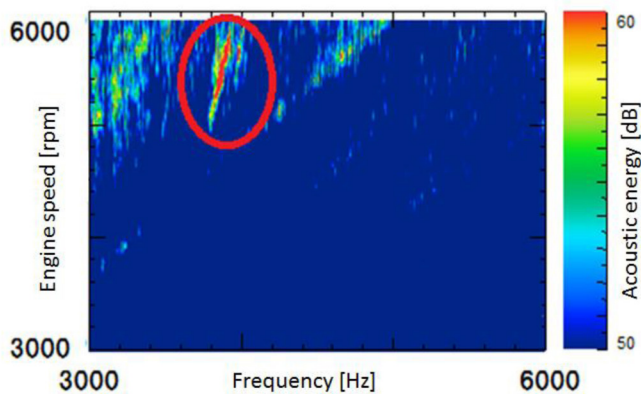


Figure 2. Results of noise measurements

Status of Simulation

The development of a method of predictive simulation of flow-induced noise would be desirable from the perspectives of the achievement of increased efficiency in the development process and the realization of increased quality. Because flow-induced noise is sensitive to minute changes in the shape of elements, including small steps and crevices and the curvature of flow paths, prediction at the drawing stage represents an issue. Conventionally, it has not been possible to evaluate whether undesirable noise will be generated until measurements are taken using prototypes. If it is judged based on measurements that correction is necessary, it is then necessary to identify the cause of the noise and modify the shape, and therefore change the design. Commercial computational fluid dynamics (CFD) software offers computation models based on steady-state calculation(2) as a method of simulating broad-band noise. However, because narrow-band noise necessitates fluid computations that take time history changes into consideration, resulting in a high computation load, the method is challenging to apply.

Sound is propagated by cyclical changes in the density of the air forming a wave motion. In order to simulate sound, it is essential to perform fluid computations of sufficient resolution to achieve an understanding of flow fields that include minute vortex flows that produce infinitesimal pressure fluctuations. In addition, components of the high-frequency band of 1,000 Hz and above are dominant in flow-induced noise (in contrast with noise generated by the vibration of structures). Simulations using computation methods such as direct numerical simulation (DNS) and large eddy simulation (LES) have been reported as useful for computing flow-induced noise(3),(4). The application of measures to the areas around the door mirrors has been reported as an effort to reduce flow-induced noise(5), but there are still few reports concerning initiatives of this type.

Computation time is also an issue associated with simulations. It was predicted that an enormous amount of computation time would be necessary for a simulation of high-frequency narrow-band noise of the type to be conducted in the present research. The advantage of simulation is the ability to consider results prior to the production of prototypes, but an enormous computation time would nullify this advantage. In the case of automotive developments, a large number of preliminary verifications by means of simulation are desirable. The demands on the simulation were therefore to realize a constant practical level of accuracy and a short computation time.

The realization of a practical level of predictive accuracy for the developed computation method has been discussed in a separate paper(6). This paper will focus on the development of a method of reducing computation time while maintaining accuracy.

Development Aims

The project aimed to develop a predictive simulation of narrow-band noise that could be applied within the automotive development period. Comparison of simulation and measurement results indicated that the simulation was a predictive method able to reproduce the measured phenomena. The subject of computation for the development of a narrow-band noise simulation was a steady-state flow test in a muffler and exhaust pipe (the combination is collectively termed “exhaust pipe” here). The internal structure of the exhaust pipe is made up of complex shapes, encompassing areas in which small holes are formed in the pipe and separators, thin pipe walls, curvature and branching of pipes, and connections between parts (Fig. 3). Because of this, there are numerous areas that represent factors in producing noise, making the identification of the noise sources an issue. In order to reproduce the phenomenon of noise production, both the measurements and the simulation employed actual rather than simplified shapes.

Given that the aim of the study was to develop a predictive method for use in the automotive development process, it was necessary to realize a level of accuracy and computation load that could be applied during development. The following three aims were established in order to develop a method displaying a practical level of accuracy and computation time for use in model development:

1. Realization of a maximum computation time of one week, to enable use in the model development process;
2. Development of a method for prediction of narrow-band noise with a predictive accuracy of within $\pm 200\text{Hz}$; and
3. Creation of benchmarks to make it possible to predict computation time in advance.



Figure 3. Internal structure of muffler

DEVELOPMENT OF ANALYSIS METHOD

Narrow-band noise occurs because there are structures in the exhaust pipe that amplify sound in specific frequency domains. The computation of this amplification mechanism necessitates the use of a method that enables the unsteady state of the flow field and the propagation of pressure to be understood at a high level of spatial resolution, rather than the conventional method, in which a time-averaged flow field is solved for use when determining the flow rate, pressure loss, and coefficient of drag. The increased computation load resulting from the extremely high mesh number needed for the use of this method represented an issue, but large-scale parallel computation dispersed the burden, making it possible to obtain a solution within a practical time frame.

Application of LES Turbulence Model

Models for the numerical computation of turbulence, generally known as turbulence models, are employed in the computation of flows. Reynolds-averaged Navier-Stokes equations (RANS) and LES are two representative turbulence models. Figures 4 and 5 compare LES and RANS. Figure 4 shows fluctuations in pressure, while Fig. 5 shows a vorticity contour diagram. RANS models and computes turbulent motion as a whole, and is mainly suited to the solution of steady-state averaged flows. LES directly computes comparatively

large vortices using the Navier-Stokes equation, and models and computes fine flows. Figures 4 and 5 show that LES is able to simulate more detailed flows than RANS, and is also more suited to the simulation of highly unsteady-state phenomena such as vortex shedding.

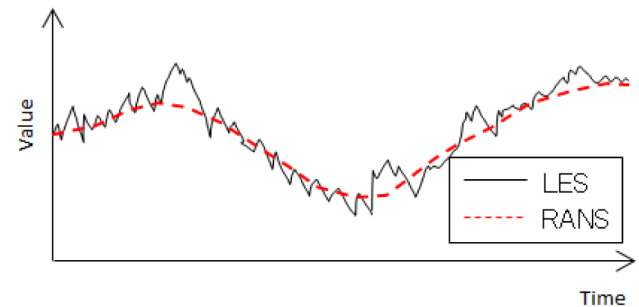


Figure 4. Comparison of LES and RANS

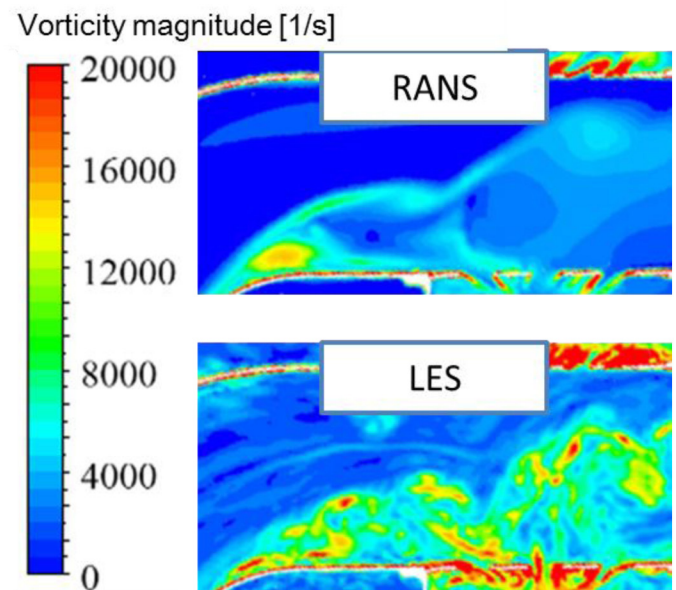


Figure 5. Comparison of LES and RANS

Consideration of Compressibility

In order to simulate the minute changes in pressure occurring as a result of the formation and dispersion of turbulent eddies, when calculating the density of the air, pressure-dependence is calculated using the equation of state of an ideal gas. Figure 6 shows the results of a simulation of cavity tones, a noise-producing phenomenon that occurs due to the rapid expansion and contraction of the curvature or the cross-sectional area of a flow channel. The impact of the eddy formed at the edge upstream in the cavity against the edge downstream in the cavity produces a sound wave. The propagated sound wave promotes the generation of a still stronger eddy at the upstream edge. The repetition of this phenomenon in a fixed cycle